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13. ABSTRACT *(Maximum 200 words)*

The achievements of previous graduate and undergraduate students and the recent technical accomplishments in our DOD-funded projects are presented to justify support for two graduate research assistants, for graduate student presentation of results at national scientific meetings, and for two undergraduate research students. This is a physics/optics research program to supplement DEPSCoRAFOSR Contract Numbers F49620-94-1-0465 for Persistent Spectral Hole Burning Materials for Time-and Frequency-Domain Optical Memories and Signal Processing' and F49620-96-1-0466 for "Very-Narrow-Line Semiconductor Lasers and Optical Clocks Based on Spectral Hole Burning Frequency Standards."

Facilities for hole burning and coherent transient research are available in our laboratory at Montana State University, and we have sixteen years of experience in this area, studying a variety of rare-earth activated materials. Our work is carried out in collaboration with Scientific Materials Corporation -- an AFOSR SBIR contractor, with Roger Macfarlane at IBM Almaden Research Center, with groups at the University of Oxford - UK, and with other groups in the US and France. Roger Macfar!ane at IBM is collaborating directly in the work proposed here.

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Final Report

ASSERT PROPOSAL - FY 1997

MATERIALS FOR OPTICAL MEMORIES, SIGNAL PROCESSING AND FREQUENCY STANDARDS

I. ABSTRACT

The achievements of previous graduate and undergraduate students and the recent technical accomplishments in our DOD-funded projects are presented to justify support for two graduate research assistants, for graduate student presentation of results at national scientific meetings, and for two undergraduate research students. This is a physics/optics research program to supplement DEPSCoR-AFOSR Contract Numbers F49620-94-1-0465 for "Persistent Spectral Hole Burning Materials for Time- and Frequency-Domain Optical Memories and Signal Processing" and F49620-96-1-0466 for "Very-Narrow-Line Semiconductor Lasers and Optical Clocks Based on Spectral Hole Burning Frequency Standards."

Optically-addressed memories and optical signal processing dramatically increase optical storage density and provide a new range of signal-processing devices.[1-4] Optical data routing in optical networks increase speed and routing agility and provide smart or active routing. Our search for new optical materials for these applications, evaluation of their properties, and studies of the ultimate limits on material performance highlight the research carried out under the *AFOSR Physics and Electronics/Optoelectronic Information Processing: Devices and Systems Program of Dr. Alan E. Craig*. We are striving to understand the atomic-scale mechanisms that determine material performance and to develop new materials for device applications. Current attention is focused on rare-earth and transition-metal ion materials, on materials for communications at 1550 nm and other semiconductor laser wavelengths, and on systems for photon gating.

Facilities for hole burning and coherent transient research are available in our laboratory at Montana State University, and we have sixteen years of experience in this area, studying a variety of rare-earth activated materials. Our work is carried out in collaboration with *Scientific Materials Corporation -- an AFOSR SBIR contractor*, with Roger Macfarlane at IBM Almaden Research Center, with groups at the University of Oxford - UK, and with other groups in the US and France. Roger Macfarlane at IBM is collaborating directly in the work proposed here.

II. RESEARCH OBJECTIVES AND PLAN

A. Overview and Accomplishments of Current Program

Our research at Montana State University focuses on persistent spectral hole burning with applications to time- and frequency-domain optically-addressed data storage, to optical signal processing, to signal routing at 1550 nm, and to ultranarrow semiconductor lasers and optical clocks. These technologies are being studied under AFOSR Contract Numbers F49620-94-1-0465 and F49620-96-1-0466 for the *AFOSR Optoelectronic Information Processing Devices and Systems Program on optical materials and devices under the direction of Dr. Alan E. Craig.* The new optical memories are expected to increase storage density by factors of a hundred to a billion, leading to advances in computers and information handling. Signal processing bandwidths of hundreds of GHz are expected. Data routing at multi-THz rates are expected for communications wavelengths at 1550 nm. Frequency sources with milli-Hz stability are under development. Materials are being developed for demonstrations and for applications.

Our research on persistent spectral hole burning and optical coherent transients is directed toward

a) studies of the atomic-scale material properties and material interaction mechanisms that establish the ultimate limits on material performance,
b) design, evaluation, and development of new materials for optical and optically-accessed memory technology, optical signal processing, optical data routing, and frequency standards
c) studies of new systems for "photon gating" of hole burning,
d) studies of materials for use with semiconductor diode lasers, and
e) provision of frequency references for stable lasers and optical clocks in communications, navigation, and computer systems.

We have recently extended spectral hole burning and coherent transient phenomena to crystals operating in the communications band at 1550 nm, using diode laser and erbium-doped fiber amplifier sources.

In time-domain devices, long optical coherence times (or dephasing times) T_2 are important because data streams must normally be stored or processed within the coherence time. Our accomplishments include publication of a Physical Review Letter[5] reporting the advance by a factor of 5 of the homogeneous optical coherence times. For $Eu^{3+}:Y_2SiO_5$ we observed dephasing times $T_2 = 2.6$ ms, corresponding to 122 Hz optical linewidths and $Q > 4 \times 10^{12}$; the ratio of inhomogeneous width to homogeneous width is 10^7, and these materials also have the potential for multi-GHz data rates. This material has recently been used by a group at SRI to demonstrate 10^{-8} bit-error rates in optical storage. We are using it to develop an ultra-stable optical frequency reference with expected stability in the milli-Hz range.

We have made contributions to understanding fundamental limits on memory readout mechanisms. For example, we have determined the mechanisms limiting homogeneous dephasing times in the best materials now available,[5] we have observed an important electromagnetic "shielding" phenomenon that reduces loss of coherence,[5] and we have studied interactions between the "reading" light beam and the optical material (the so-called instantaneous spectral diffusion effect).[6-13]

We have completed an extensive study of $Pr^{3+}:Y_2SiO_5$ and have shown that this is the best available host for Pr^{3+}.[11] We have studied $Eu^{3+}:Y_2O_3$ and found its dephasing properties to be more ideal than those found by other investigators. We have studied $Tm^{3+}:Y_2Si_2O_7$,[12] $Tm^{3+}:Y_2SiO_5$,[13] garnets Tm^{3+}:YAG, Tm^{3+}:YGG, Tm^{3+}:YLuAG, and Tm^{3+}:LuAG, and $Tm^{3+}:Y_2O_3$ for memory and signal-processor applications with semiconductor lasers, and we are studying a number of new materials.

We have filed a patent application.

Evaluation of new materials synthesized by Scientific Materials Corporation is a special role that we assume in the *AFOSR Optoelectronic Information Processing Devices and Systems Program of Dr. Alan E. Craig*. With Scientific Materials we are actively participating in the design of the materials. We cooperatively optimize the material properties through the close interaction with Scientific Materials made possible by our location; by providing rapid feedback, adjustments may be made to the synthesis process, leading to development of better quality materials. Characterized samples are forwarded to other groups funded by AFOSR with the specific mission to use them to develop designs for practical devices. Graduate students and undergraduates are important to this work.

We are also applying these ideas and materials to the development of other basic building blocks for modern electronic systems: frequency standards and "clock" modules. New compact devices that can serve as frequency standards are needed in the optical frequency range, and many of the applications require stabilities in the *milli*-Hz range (mHz). Until now, those optical devices have been constructed using gas-phase frequency standards requiring several large laboratory tables for realization. We propose instead to use solid state persistent-spectral-hole-burning materials as the basis for the frequency standard, developed initially in laboratory environments, but applicable in compact packages for deployment in the field. The applications are relevant to the broad field of coherent optics, to optical communications systems, and to optical computers -- both generally and particularly including time-domain optical storage and signal processing with hole burning materials. The proposed optical frequency standard is made up of a frequency reference and a compact semiconductor laser locked to that reference. Our group has recently observed optical homogeneous linewidths as small as 122 Hz,[5] a value that could provide a frequency-locking "reference" of the accuracy required for mHz laser frequency stabilization.

B. Summary of Request and Justification

This proposal is written a) to support the training of two additional graduate students to keep pace with the production of new materials and expansion of applications development, b) to provide opportunities for these graduate students to present research results at national scientific meetings, and c) to support involvement of two undergraduate students in our research. Part of the travel funding is to send the graduate students to a course in Santa Clara California on running our Coherent 899-21 Ti:sapphire laser. This is a Physics/Optics research program.

Two Ph.D. students will be supported by this AASERT project and will devote full time to these DoD-funded projects. Current graduate students working on the AFOSR project are supported by an NSF grant that expires after this year. Under the supervision of Professor Cone, the AASERT graduate students will carry out the research outlined in Sec. II.A above. They also will gain *practical industrial experience* through collaboration with the crystal growth projects of Ralph Hutcheson and Randy Equall of Scientific Materials Corporation in Bozeman and with Roger Macfarlane of IBM Almaden Research Center (a formal agreement has been made between MSU and IBM Almaden Research Center). They will collaborate with Dr. M. J. M. Leask of Oxford and will interact with other visitors to the MSU laboratory. Leask makes yearly visits funded by NATO and spent part of his sabbatical with our group at MSU in Autumn, 1995.

The requested funding will allow two undergraduates to be employed on the project full time during the summer months and will allow them to devote greater time to this project during the academic year. Undergraduate students are engaged in our research during this academic year, and their activities indicate the type of opportunities that we can offer undergraduates. Two are physics majors who are directly

engaged in recording and analysis of optical spectra of the memory materials and other crystals that we study; they learn laser operation, spectroscopic methods, computer programming, cryogenics, optics, electronics, and data analysis. The data they gather expedites the work of the graduate research assistants and the principal investigator. Two electrical engineering undergraduates have designed and built an "interferometric fringe-counting wavemeter" to measure the wavelength of our tunable lasers to one part in 10^8, an order of magnitude more accurately than commercially-available devices; that project combines physics, optics, and electronics.

The MSU Physics Department has over twenty faculty and approximately fifty graduate students and fifty undergraduate students. Cone's group has four graduate students this year, with a fifth arriving from France in February, 1997. Cone has directed seven Ph.D. theses; careers of those students are summarized later in this section.

Cone's group is one of six laser-optics groups in the MSU "OpTeC" Center of Excellence, with three Physics Faculty, two Chemistry Faculty, and an Electrical Engineer. Lee Spangler, a physical chemist, also studies rare earth crystals; J. L. Carlsten, a physicist, specializes in stabilized tunable diode lasers, super-cavity laser diagnostics, and nonlinear optics; Aleksander Rebane, a physicist studies holography and hole burning, and David Singel specializes in magnetic resonance spectroscopy of laser and hole burning materials. An additional faculty member in optics will be added to Electrical Engineering this year. Weekly to bi-weekly optics seminars are organized for the approximately 30 members of OpTeC. There are *six significant optical companies in Bozeman and a number of smaller ones, including ILX Lightwave -- diode laser specialists who have loaned us an erbium doped fiber amplifier and other instrumentation, Big Sky Laser Technologies -- solid state laser manufacturers and optical damage consultants, Scientific Materials Corporation -- rare earth crystal growth specialists providing materials to us and to other members of Alan Craig's program, Wavelength Electronics -- diode laser instrumentation, and Lattice Materials Corporation -- infrared optical materials.*

To enhance students' interactions with local optical industries and to give them experience making conference presentations, a two-day Conference on Optical Science and Laser Technology is sponsored annually by the MSU Departments of Physics, Chemistry, and Electrical Engineering, and the local optics companies. On the first day, three outside scientists, five MSU principal investigators, and representatives of five local companies present talks, while on the second day, typically 20 student papers are presented. This year Dr. John Hall of JILA, acknowledged expert on laser stabilization, accepted our invitation to participate in this conference. Other external participants were Todd Yeates of Wright Patterson Air Force Base and Kevin Lear of Sandia Laboratories.

<u>Ph.D. graduates from Cone's laboratory:</u>

1) David A. Ender, 3M Corporate Research Laboratory -- nonlinear optical materials research (Minnesota, Mining, and Manufacturing), St. Paul, Minnesota.
2) Michael S. Otteson, MIT Spectroscopy Laboratory -- laser applications, Cambridge, Massachusetts.
3) Jin Huang, Department of Physics, University of Oregon, Post-Doctoral Position -- hole burning and laser spectroscopy, Eugene, Oregon, now on faculty of University of Wisconsin at Eau Claire.
4) Guokui Liu, Chemistry Division, member of technical staff, Argonne National Laboratory -- hole burning and laser spectroscopy of actinide compounds, Argonne, Illinois.
5) Yongchen Sun, Department of Physics and Astronomy, University of Georgia, Post-Doctoral Position -- UV and laser spectroscopy, Athens, Georgia.
6) Randy W. Equall, received offers from Intel Corporate Research Laboratory and Scientific Materials Corporation -- Currently at Scientific Materials Corporation.

7) Guangming Wang, accepting a post doctoral position at Chemistry Division, Argonne National Laboratory -- optically detected nuclear magnetic resonance spectroscopy of actinide compounds, Argonne, Illinois.

Masters of Science graduates from Cone's laboratory:

1) Paula Louise Fisher-Darejeh, Hewlett-Packard -- photolithography development, Fort Collins, Colorado.
2) James Boger, physics teaching at Oregon Institute of Technology, Klamath Falls, Oregon.
3) Raymond Jones, laser development, Big Sky Laser Technologies, Inc., Bozeman, Montana.

Bachelors of Science graduates from Cone's laboratory:

1) Roy Nelson, graduate study at Institute of Optics, University of Rochester, to Rocketdyne Corporation and then Ball Research Laboratory, Boulder, Colorado.
2) Kevin Kilty, graduate study at University of Utah.
3) Jim Brug, graduate study at Yale University, then to Hewlett-Packard Research Laboratory, Palo, Alto, California.
4) Joe Sullivan, Rocketdyne Corporation, California.
5) William Tolbert, graduate study at University of Wisconsin and Post-Doctoral research at University of Illinois.
6) Jon Eggert, graduate study at Harvard University, Cambridge, Massachusetts.
7) Sean Dirkes, aerospace industry.
8) Charles Thiel, 1995 Congressional Barry M. Goldwater Scholar.
8) Tyler Morgus, graduate study at Lehigh University.

Clearly, all of these students have contributed to the AASERT goals by playing important roles as scientists and engineers.

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III. QUALIFICATIONS OF PRINCIPAL INVESTIGATOR

Professor Rufus L. Cone

Cone has twenty years experience with rare earth spectroscopy and ion-ion interactions and has established connections with a number of other laboratories. His group has fourteen years experience in spectral hole burning, optical coherent transient experiments, and other nonlinear optical techniques, studying a variety of rare-earth-activated materials. Excellent facilities for photon echo and hole burning research are available in Cone's laboratory. His contributions to the area of this proposal are acknowledged by invitations to present invited talks at the 1996 International Conference on Luminescence in Prague, the 1996 International Meeting on Hole Burning and Related Spectroscopies, several AFOSR Workshops on Persistent Spectral Hole Burning, 1996 AFOSR Contractors Workshop on Time and Frequency Standards at Phillips Laboratory, 1994 Annual Meeting of the Optical Society of America, at a 1994 International Workshop on Laser Physics entitled "Transient Coherent Phenomena," at three Rare Earth Research Conferences - including July 7-12, 1996, and at 1989 International Conference on Dynamical Processes in Excited States of Solids. He has authored a comprehensive review of ion-ion interactions.